

NISTIR 5090

U.S. DEPARTMENT OF
COMMERCE

Technology
Administration

National Institute of
Standards and Technology

NIST

**Electronics and Electrical
Engineering Laboratory**

Optoelectronics Division

**Programs, Activities, and
Accomplishments**



The Electronics and Electrical Engineering Laboratory

Through its technical laboratory research programs, the Electronics and Electrical Engineering Laboratory (EEEL) supports the U.S. electronics industry, its suppliers, and its customers by providing measurement technology needed to maintain and improve their competitive position. EEEL also provides support to the federal government as needed to improve efficiency in technical operations and cooperates with academia in the development and use of measurement methods and scientific data.

EEEL consists of five programmatic divisions and two matrix-managed offices:

- Electricity Division
- Semiconductor Electronics Division
- Radio-Frequency Technology Division
- Electromagnetic Technology Division
- Optoelectronics Division
- Office of Microelectronic Programs
- Office of Law Enforcement Standards

This document describes the technical programs of the Optoelectronics Division. Similar documents describing the other Divisions and Offices are available. Contact NIST/EEEL, 100 Bureau Drive, MS 8100, Gaithersburg, MD 20899-8100, Telephone: (301) 975-2220, On the Web: www.eeel.nist.gov.

Cover Caption: The Optoelectronics Division supports the optoelectronics industry by providing new measurement techniques and standards to help characterize and assure the quality of their products. Examples shown here are laser power measurements for eye surgery, optical polarization changes in compact discs, miniature laser sources for optical fiber telecommunications, and transmission losses for the many-kilometer lengths of optical fiber.

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January 2000

U.S. DEPARTMENT OF COMMERCE

William M. Daley, Secretary

Technology Administration

Dr. Cheryl L. Shavers, Under Secretary of Commerce for Technology

National Institute of Standards and Technology

Raymond G. Kammer, Director



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Welcome

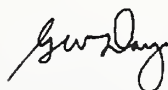
Optoelectronics is the merger of optics and electronics in which devices such as lasers, detectors, and optical fibers have enabled many familiar and diverse high technology products and processes: high quality telephone systems, the Internet, laser printers, fax machines, compact disc technology for consumer electronics and computer storage, retail checkout systems, advanced medical procedures, and new methods of manufacturing. Optoelectronics is a cornerstone of the Information Age and a large international business with intense competition. The worldwide market for optoelectronic components is currently around \$50B, roughly one third of the size of the market for electronic components, and growing rapidly. The market for equipment enabled by optoelectronic components approaches \$200B.

Our job in the NIST Optoelectronics Division is to provide the optoelectronics industry with the measurement technology, standards, and traceability that it needs to grow and be competitive. Through a series of studies, the Optoelectronics Industry Development Association (OIDA) has concluded that metrology is one of the four key elements of manufacturing infrastructure in which investment needs to be made if the U.S. optoelectronics industry is to maintain or expand its competitive position in optoelectronics.

Since the late 1960s, we have maintained the U.S. national standards for laser power and energy measurement and provided the industry with calibration services for detectors and power meters used with lasers. Since the late 1970s we have worked with the optical communications industry to develop measurement methods and Standard Reference Materials (artifact standards) to support the specification of optical fiber and other components. We now also work with the optical fiber sensor industry, the optical data storage industry, the semiconductor industry, and the medical electronics community to provide the metrology needed in these fields. Increasingly, our work is directed toward metrology that can enable more efficient manufacturing of optoelectronic components and materials.

We are a team of about 60 scientists, engineers, and support staff, located in the NIST Boulder Laboratories, in Boulder, Colorado. We invite you to contact us to discuss our current work as well as your needs for metrology. You will find our names and points of contact on page vi and on our web site (<http://www.boulder.nist.gov/div815>), where you will also find additional information about our work and the services we provide to the industry.

Thank you for your interest in the Optoelectronics Division.



Gordon W. Day
Division Chief

About the Optoelectronics Division

Mission

The mission of the Optoelectronics Division is to provide the optoelectronics industry and its suppliers and customers with comprehensive and technically advanced measurement capabilities, standards, and traceability to those standards.

History

The Division is located in Boulder, Colorado, as a part of the NIST Boulder Laboratories. It was established in 1994, succeeding an earlier NIST organizational unit, the Optical Electronic Metrology Group of the Electromagnetic Technology Division. The Division's roots extend to the first NIST (NBS) work on optoelectronics--research begun in the early 1960s to develop techniques for measuring the output power, or energy, of a laser. Since the late 1960s, NIST research on measurement and standards to support the development and application of lasers has been centered in the Boulder Laboratories. Research related to optical communications was added in the mid 1970s, and expanded substantially in the late 1980s; it now represents more than half of the Division's effort.

Organization

The Division is organized into four Groups. Three Groups focus on the characterization of optoelectronic components--the Sources and Detectors Group, the Fiber and Integrated Optics Group, and the Optical Components Group. The fourth Group--the Optoelectronic Manufacturing Group--focuses on measurements that can lead to more efficient manufacturing of optoelectronic materials and components.

Research and Services

Most of the research performed in the Division is conducted either with NIST appropriated funds or under contract to other U.S. Government agencies. Results are normally placed in the public domain through publication in the open literature. Some results become the subject of patents, and are available for license. The Division also conducts proprietary research in collaboration with industry and universities through Cooperative Research and Development Agreements (CRADAs).

The Division and its predecessor organizations have been providing calibration services for the characterization of lasers and detectors since 1967, and each year conducts over 100 calibrations for about 50 customers. It also provides the industry with standard reference materials, which are artifact standards that can be used to calibrate a customer's own instrumentation.

The Division maintains close contact with the optoelectronics industry through major industry associations, including the Optoelectronics Industry Development Association (OIDA), the Lasers and Electro-optics Manufacturer's Association (LEOMA), and the Optical Disc Manufacturer's Association (ODMA). Division staff members represent NIST to the major domestic and international standards organizations active in optoelectronics-- the Telecommunications Industries Association (TIA), the International Electrotechnical Commission (IEC), the International Organization for Standardization (ISO), and the

American National Standards Institute (ANSI)– and provide impartial technical expertise in their negotiations.

Courses and Conferences

The Division offers an annual Short Course on Laser Measurements and biennially organizes a major international conference on optoelectronic measurements, the Symposium on Optical Fiber Measurements.

Optoelectronics Division Organization

Division Office (815.00)

5204	DAY, Gordon W., Chief	3288	McCOLSKEY, Kathy S., Administrative Officer
5202	CLARK, Alan F., Deputy Chief		
5342	SMITH, Annie J., Secretary	5123	DERR, Linda S., Administrative Assistant

Sources and Detectors (815.01)

3651	SCOTT, Thomas R. (GL)
3842	SKINNER, Dorothy L., Secretary

Laser Radiometry

5620	CROMER, Christopher L. (PL)
3741	CASE, William E. (CTR)
7455	DOWELL, Marla L.
3439	JONES, Richard D.
5583	KEENAN, Darryl A.
3654	LEHMAN, John H.
3621	LI, Xiaoyu
5898	LIVIGNI, David J.
3696	PHELAN, Robert J., Jr. (CTR)
3394	VAYSHENKER, Igor
	ZHANG, Zhoumin (CTR)

High-Speed Measurements

5367	HALE, Paul D. (PL)
3741	CASE, William E. (CTR)
3052	CLEMENT, Tracy S. (PT)
5162	LEONHARDT, Rodney W.
5747	OBARSKI, Gregory E.
3749	SIMPSON, Philip A. (CTR)
5253	TOBIAS, Iris L.
3193	VERDONI, Angelo P. (S)

Fiber and Integrated Optics (815.02)

3805	WILLIAMS, Paul A. (Act. GL)
5187	METZ, Sara E., Secretary

Optical Fiber Metrology

3805	WILLIAMS, Paul A. (PL)
5858	DRAPELA, Timothy J.
	GARCIA, Jose (GS)
	MECHELS, Steven E. (PT)
3542	SCHLAGER, John B.
3549	TAKARA, Hidehiko (GS)
3223	YOUNG, Matt (PT)

Integrated Optic Metrology

3223	YOUNG, Matt (PL)
	FONTAINE, Norman H. (PD)
3289	FUNK, David S.
3250	KALRA, Punit S. (S)
	MECHELS, Steven E.

Optical Components (815.03)

3120	GILBERT, Sarah L. (GL)
3842	SKINNER, Dorothy L., Secretary

Optical Fiber Sensors

5170	ROCHFORD, Kent B. (PL)
7463	DYER, Shellee D. (PD)
7630	ESPEJO, Robert J. (S)
7630	FEAT, Nicolas (GS)
7367	KREGER, Stephen T. (PD)
7630	KUNKEL, Kari L. (S)
5599	ROSE, Allen H.
7612	SORNSIN, Elizabeth A. (PD)

Fiber and Discrete Components

3120	GILBERT, Sarah L. (PL)
3359	CRAIG, Rex M.
3507	DENNIS, Tasshi (PD)
3287	ETZEL, Shelley M. (PT)
5009	HUBBARD, Margaret A. (PD)
7381	SWANN, William C.

Optoelectronic Manufacturing (815.04)

3455	HICKERNELL, Robert K. (GL)
5187	METZ, Sara E., Secretary

Dielectric Materials and Devices

5239	SANFORD, Norman A. (PL)
3942	AUST, J. Andrew
3289	FUNK, David S. (PD)
	McCOY, Michael A. (GS)
7703	MITCHELL, Jeff (S)
7300	PETERS, Phil M. (PD)
5420	ROSHKO, Alexana
5952	VEASEY, David L.

Semiconductor Materials and Devices

3455	HICKERNELL, Robert K. (PL)
5069	BERTNESS, Kristine A.
3354	CHRISTENSEN, David H.
3234	HAYS, Scott (S)
	KNOPP, Kevin J. (S)
7955	MIRIN, Richard P.
7948	SILVERMAN, Kevin L. (S)
7953	SUMAN, Christopher C. (PT)

Legend:

CTR = Contractor
GL = Group Leader
GS = Guest Scientist
PD = Postdoctoral Appointment
PL = Project Leader
PT = Part Time
S = Student

Telephone numbers are:
(303) 497-XXXX, (the four
digit extension as indicated)

Laser Radiometry

Technical Contact:
Christopher L. Cromer

Staff-Years:
7.75 professionals
1.0 technician
3.0 contractors

Funding Sources:
NIST (73 %)
Other Government Agencies (19 %)
Calibration fees (8 %)

Parent Program:
Optoelectronics

Project Goals

Develop measurement methods and standards for characterizing laser sources and detectors used with continuous-wave (CW) and pulsed laser radiation. Develop and maintain measurement services for laser power and energy, optical fiber power, and related parameters (e.g., spectral responsivity, linearity, etc.).

Customer Needs

Accurate characterization of optoelectronic sources and detectors is important in the development and use of industrial technologies such as lightwave telecommunications, laser-based medical instrumentation, materials processing, photolithography, data storage, and laser safety equipment. This Project focuses on selected critical parameters intrinsic to optoelectronic sources and detectors, specially the calibration of optical fiber power meters and laser power or energy meters at commonly used wavelengths and powers or energies. In addition, special test measurements are available for linearity, spectral responsivity, and spatial uniformity of laser power meters and detectors. In support of source characterization, measurement methods are developed to evaluate and characterize beam intensity profile and propagation of laser beams. The semiconductor photolithography and corneal sculpting markets require pulsed excimer laser measurements. Project members participate in national and international standards committees developing standards for laser safety, laser radiation measurements (such as beam profile and pointing stability), and optical-power-related measurements. They extend and improve source and detector characterizations, including development of low noise, spectrally flat, highly uniform pyroelectric detectors, high accuracy transfer standards for optical fiber and laser power measurements, and advanced tunable laser systems for laser power and energy measurement systems.

Technical Strategy

To meet the needs of the laser and optoelectronics industries and to anticipate emerging technologies requires investigation and development of improved measurement methods and instrumentation for high-accuracy laser

metrology over a wide range of powers, energies, and wavelengths.

NIST has historically used electrically calibrated laser calorimeters to provide traceability to the SI units for laser power and energy. We recently developed a new measurement capability based on a Laser Optimized Cryogenic Radiometer (LOCR) which provides an order of magnitude improvement in accuracy for laser power measurements. To meet the increasingly demanding needs of higher accuracy, it is necessary to improve accuracy of calibration services through development of better transfer standards traceable to LOCR.

MILESTONE: By 2002, reduce the uncertainties for all laser energy and power, and optical fiber power calibrations supplied to customers by at least a factor of 2. This will be accomplished through the development of improved transfer standards and instrumentation to characterize these devices and accurately assess uncertainty budgets.

Advances in laser technology are continuously producing lasers with new wavelengths and power levels. We are involved in an ongoing effort to expand wavelength and power range capabilities through implementation of new solid-state laser technology to keep up with customer needs for calibration services at NIST.

MILESTONE: By 2002, develop a tunable solid-state laser system to cover the entire spectral range from the deep UV to the thermal IR. This laser system will continue to evolve as new technology becomes available to provide new calibration services as needs arise.

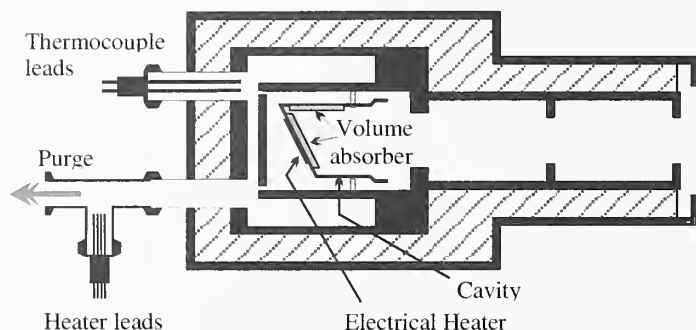
The semiconductor industry is now investigating the use of F₂ excimer lasers at 157 nm for the next generation of photolithography tools for computer chip manufacturing. A new primary standard pulsed-laser calorimeter designed for the 157 nm operation is needed to provide the basis for a calibration service at this wavelength.

MILESTONE: By 2001, develop a 157 nm excimer laser primary standard and calibration service to provide support for semiconductor photolithography.

Currently NIST provides calibrations for excimer laser power and energy meters at 248 nm and 193 nm to laser and meter manufacturers. End users of the excimer laser meters often need energy

density (dose) measurement capabilities as well. For example, semiconductor photolithography tools for chip manufacturing use small-area detectors to monitor photoresist exposure levels.

MILESTONE: By 2001, develop the capability at NIST of calibration services for energy density (dose) meters at 248 nm and 193 nm.



Excimer laser calorimeter for 193 nm.

Optical materials for ultraviolet excimer laser applications require special measurement techniques and conditions. For example, the transmittance of synthetic quartz at 193 nm is changed by laser cleaning of the sample surface during measurements with high energy excimer laser beams. In addition, other optical parameters such as strain induced birefringence are critical for the design and characterization of optical components in semiconductor photolithography tools.

MILESTONE: By 2001, develop capabilities at NIST for characterization and measurement of parameters such as transmittance and birefringence of DUV optical materials for excimer laser applications.

With the rapid development of wavelength division multiplexing (WDM) technology for optical fiber communications, the range of available diode laser wavelengths has increased dramatically. Calibration services at NIST will be required by the communications industry to support this new technology. Currently NIST uses a lamp/monochromator-based system to fill in the gaps in the wavelength coverage for optical fiber power meter calibrations, but this system is not optimum for providing high-accuracy optical fiber power meter calibrations. Research in diode laser technology using multiple quantum well structures (MQW) has demonstrated tuning ranges of greater than 100 nm. To meet the increasing demands for higher accuracy and wider wavelength coverage, NIST needs to

implement these advances in tunable diode laser systems for calibration services applications.

MILESTONE: By 2002, develop tunable diode lasers based on MQW technology with very large tuning range for optical fiber power meter calibrations.

Accomplishments

■ Improved accuracy of fiber optic power meter calibrations by a factor of two.

Completed a DOD funded project to improve fiber optic power meter calibrations. Using a high accuracy laser-optimized cryogenic radiometer (LOCR), succeeded in reducing the uncertainty of calibration services from 1 % to 0.5 %.

Significance: Improved accuracy for the NIST calibrations will enable higher accuracy for end users, and will result in tighter tolerances in optical fiber communication systems. DOD is investing heavily in fiber optic systems in many applications such as electromagnetic pulse (EMP) resistance, weight reduction, and high-speed communications.

■ **193 nm excimer laser power and energy meter calibration services.** With partial support from SEMATECH, completed development of a new DUV primary standard calorimeter for measurement of 193 nm excimer laser pulse energy. Established a new service to calibrate customer power and energy meters for 193 nm excimer lasers with an uncertainty of ~ 1 %. (Collaboration with NIST Division 844 and MIT Lincoln Laboratory).

Significance: Standards traceable to SI units for DUV excimer laser pulse energy are important for medical applications such as excimer laser eye surgery, and for the semiconductor industry for accurate process control in computer chip manufacture.

■ DUV excimer laser beam attenuator.

Developed novel multi-reflection attenuator for DUV excimer lasers with improved stability over traditional attenuators that use bulk material absorption. Enables adjustment of the laser energy without disturbing other laser beam characteristics. (Collaboration with NIST Division 844 and MIT Lincoln Laboratory).

Significance: Accurate measurements using DUV excimer lasers require the adjustment of the laser energy and power in a stable and repeatable way. This cannot be accomplished easily with the laser control system, since the laser becomes unstable near threshold.

- **DUV excimer laser transmittance of optical materials.** Developed a measurement system for the transmittance of optical materials (e.g., fused silica and calcium fluoride) using a 193 nm excimer laser. Measurements are performed in a nitrogen gas environment with an uncertainty of < 1 %, and are available to customers as a special test. (Collaboration with NIST Division 844 and MIT Lincoln Laboratory).

Significance: Applications for 193 nm excimer lasers require accurate transmittance measurements of system components to assure performance and to meet design tolerances. Industry measurements of transmittance using both excimer lasers and traditional spectrophotometers show considerable disagreements (~ 5 %).

- **Improved radiometer using domain-engineered pyroelectric detector element.** Developed improved radiometer for optical measurements using domain-engineered pyroelectric detector element. Reduced susceptibility to environmental acoustic noise and vibration, resulting in lower noise floor for optical measurements in most applications. (Collaboration with Division 844).

Significance: Improves the general performance of pyroelectric detectors in optical measurements at NIST and other optical metrology labs.

- **High power calibration of optical fiber power meters at 980 nm.** Added measurement capability for optical fiber power meter calibrations at 980 nm up to 150 mW.

Significance: Required by new industries involved in manufacture of pump laser sources for erbium fiber lasers and amplifiers used in new WDM communications applications.

FY Deliverables

Calibrations

66 calibrations performed on 107 items for 27 customers.

Standards Committee Participation

American National Standards Institute/Z136: Thomas R. Scott and John H. Lehman are members of this committee, which deals with Safe Use of Lasers.

International Organization for Standardization/TC172/SC.09: Thomas R. Scott is a member and US delegation leader of this committee, which deals with Electrooptical Systems.

Optics and Electro-Optics Standards Council/-CO04: Thomas R. Scott is a member of this committee, which deals with IEEE-LEOS.

U.S. National Committee of the International Electrotechnical Commission/TC076: Thomas R. Scott is a member of this committee, which deals with Laser Equipment.

Telecommunications Industry Association/FO06/SC.01/WG.10: Igor Vayshenker is a member of this working group, which deals with Metrology and Calibration.

Publications

"A Transfer Standard for Optical Fiber Power Metrology," J. Lehman, X. Li; Opt. & Phot. News, Eng. and Lab. Notes 10, No. 5, pp. 44f-h (May 99)

"Thermal Characterization of a Cryogenic Radiometer and Comparison with a Laser Calorimeter," D.J. Livigni, C.L. Cromer, T.R. Scott, B.C. Johnson, Z.M. Zhang; Metrologia 35, No. 6, pp. 819-827 (Mar 99)

"Heat Transfer Analysis and Modeling of a Cryogenic Laser Radiometer," B.C. Johnson, A.R. Kumar, Z.M. Zhang, D.J. Livigni, C.L. Cromer, T.R. Scott; J. Thermophysics and Heat Transfer 12, No. 4 (Dec 98) "Deep Ultraviolet Laser Metrology for Semiconductor Lithography," M.L. Dowell, C.L. Cromer, R.W. Leonhardt, T.R. Scott; Proc., 1998 Int'l Conf. on Characterization and Metrology for ULSI Tech. 449, pp. 530-541 (Nov 98)

"Silicon Wedge-Trap Detector for Optical Fibre Power Measurements," J. Lehman, J. Sauvageau, I. Vayshenker, C. Cromer, K. Foley; Meas. Sci. Technol. 9, No. 10, pp. 1694-1698 (Oct 98)

High-Speed Measurements

Technical Contact:
Paul D. Hale

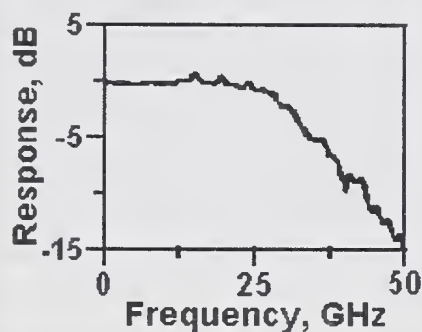
Staff-Years:
4.0 professionals
0.5 technician
1.0 contractor
1.0 student

Funding Sources:
NIST (73 %)
Other Government Agencies (25 %)
Calibration Fees (2 %)

Parent Program:
Optoelectronics

Project Goals

Provide advanced metrology, standards and measurement services relating to temporal properties of optical sources and detectors used in association with optoelectronic systems.



Frequency response of optical communications receiver, obtained with swept-frequency heterodyne measurement system.

Customer Needs

High-bandwidth measurements are needed to support high-performance systems that take advantage of the potential bandwidth of optical fiber. Systems presently being installed operate at 5 to 10 gigabits per second using pure optical time division multiplexing (OTDM). Research is being done on the next generation of OTDM systems at 20 to 40 gigabits per second in laboratories around the world. Methods are needed to characterize the scalar and vector frequency response of high-speed sources and detectors to at least the third harmonic of the system modulation rate. Burst mode operation in asynchronous transfer mode networks requires additional characterization at very low frequencies. Increasingly tight tolerances in both digital and analog systems require frequency response measurements with low uncertainty.

Source and detector noise measurements are required to predict low bit error rates in computer interconnects, high carrier-to-noise ratios in analog systems, and to support erbium-doped fiber amplifier noise figure measurements.

The intensive use of laser target designators and range finders by the armed forces requires traceable low-level pulse peak power and energy calibration standards at 1064 nm and 1550 nm.

Technical Strategy

NIST has developed highly accurate heterodyne techniques at 1319 nm for measuring detector frequency response and is extending this capability to 850 nm. High-speed optoelectronic system design requires measurement of the phase response of optoelectronic components.

Researchers in the High-Speed Measurements Project are developing time-domain techniques for measuring optoelectronic phase response with verifiable accuracy.

NIST is developing standards for calibrating optical noise measurement systems, which use an optical spectrum analyzer or measure relative intensity noise (RIN).

NIST has developed methods for calibrating absolute laser pulse energy and peak power which are traceable to national cw laser power and energy standards maintained by the Sources and Detectors Group.

MILESTONE: By 2002, have Calibration Service available for optoelectronic phase at 1550 nm.

The vector optoelectronic frequency response of a photoreceiver determines its impulse response. At present there are no accepted methods for measuring optoelectronic vector frequency response.

MILESTONE: By 2001, have certified optical noise sources available for calibrating RIN and optical noise power spectral density.

Measurements of laser and optical amplifier noise are commonly made by use of a RIN subtraction technique or by several methods that use an optical spectrum analyzer. RIN and optical power spectral density standards would calibrate the fundamental quantity that is being measured in all of these methods.

MILESTONE: By 2001, have Calibration Service available for 1550 nm low-level peak pulse power and pulse energy.

Pulse power and energy measurements are required for a new generation of eye-safe laser target designators and range finders.

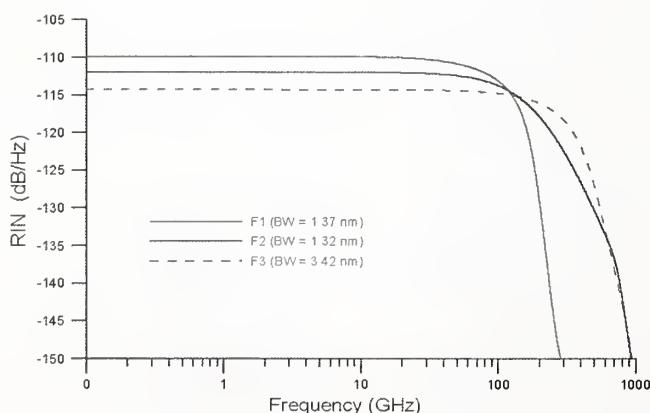
MILESTONE: By 2001, have Calibration Service available for 850 nm optoelectronic scalar frequency response.

The recent explosion of high-speed interconnect applications that use multimode fiber and laser sources in the 750 nm to 850 nm wavelength region has greatly increased the need for test equipment for these systems. This includes reference receivers with well-characterized frequency response between about 1 MHz and 10 GHz. Since 10 gigabits per second systems are being considered by several companies, and since components may need to be characterized to three times the bit rate, future needs may extend above 30 GHz.

Accomplishments

- A detailed uncertainty analysis of a 1319 nm heterodyne scalar frequency response measurement system was completed. This analysis was used as the foundation of a new Calibration Service for transfer standards, which is a fast photodiode combined with a rf power sensor. The combined stability of the heterodyne calibration system and a transfer standard was studied over one year.

- A detailed uncertainty analysis of a RIN standard was completed. The standard consists of an erbium-doped fiber amplifier, narrow-band optical filter, and polarizer, and provides an amount of noise that can be calculated from first principles. After final procedural documentation and approval NIST will provide a Measurement Assurance Program for RIN.



RIN spectrum of three separate sources calibrated from fundamental physical principles.

- As part of the program to measure optoelectronic vector frequency response, a multidisciplinary collaboration between the Optoelectronics, Radio Frequency Technology, Statistical Engineering, and Electricity Divisions built the necessary procedures and algorithms to

perform nose-to-nose calibration of high-speed digital sampling oscilloscopes. The procedures include time-base distortion measurement and correction, drift measurement and correction, signal alignment, mismatch correction, and nose-to-nose deconvolution.

- A new integrated software package for automatic data acquisition and control for the 1064 nm and 1550 nm low-level radiometer calibration systems was completed and tested. Previous data acquisition in the 1064 nm system was performed mostly manually and the software has greatly reduced the time required for calibration. In addition, the software supports the new 1550 nm system.

FY Deliverables

Calibrations

10 calibrations performed on 10 items for 7 customers.

Standards Committee Participation

Telecommunication Industry Association/FO02/SC.01/WG.01: Gregory Obarski is a member of this working group, which deals with Optical Amplifiers.

Telecommunication Industry Association/FO06/SC.01/WG.10: Gregory Obarski is a member of this working group, which deals with Metrology and Calibration.

Publications

"How to Measure Relative Intensity Noise in Lasers." G.E. Obarski, P.D. Hale; *Laser Focus World* 35, No. 5, pp.273-277 (May 99)

"Instantaneous and Noninstantaneous Nonlinear Effects in Femtosecond Pulse Propagation," H.K. Eaton, S.A. Diddams, A.A. Zozulya, A.G. Van Engen, T.S. Clement; *Proc., Int'l Soc. for Opt. Eng., Optical Pulse and Beam Propagation* 3609, pp. 152-160 (Jan 99)

"Unraveling the Mysteries of Intense Femtosecond Pulse Propagation," S.A. Diddams, H.K. Eaton, A.G. Van Engen, A.A. Zozulya, T.S. Clement; *Opt. & Phot. News* 9, "Optics in 1998," No. 12, pp. 37-38 (Dec 98)

"Investigations of Nonlinear Femtosecond Pulse Propagation with the Inclusion of Raman, Shock and Third Order Phase Effects," A.A. Zozulya, S.A. Diddams, T.S. Clement; *Phys. Rev. A* 58, No. 4, pp. 3303-3310 (Oct 98)

Fiber Optics Metrology

Technical Contact:
Paul A. Williams

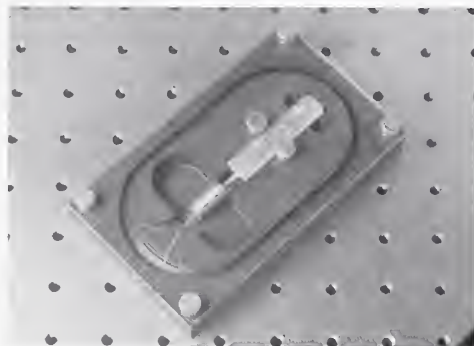
Staff-Years:
3.0 professionals
1.0 guest scientist

Funding Sources:
NIST (82 %)
Other Government Agencies
(18 %)

Parent Program:
Optoelectronics

Project Goals

Provide measurements, standards, and expertise to support fiber optic characterization for the optical telecommunications industry.



Optical fiber mode-field diameter artifact (SRM 2513).

Customer Needs

The mature fiber optic market faces continuing metrology challenges imposed by demands for higher overall data transmission rates. Increased time-domain data rates push the need for characterization of fiber's dispersive properties; wavelength division multiplexing implementations require continuing improvements in measurements of spectral and nonlinear properties.

Technical Strategy

As multimode networks change from LED sources to laser sources, launch conditions become less well defined and predictions of bandwidth performance are much less reliable. This year, we will use variable-launch impulse response measurements to generate a map between differential-mode delay measurements on fibers and their predicted systems-level bandwidth performance.

Recent industry inter-laboratory comparisons have shown poor agreement for spectral gain measurements of erbium-doped fiber amplifiers (EDFA). We will refine our measurement capability and amplified stimulated emission (ASE) reduction techniques to provide a characterized artifact standard for EDFA spectral gain.

Milestone: By 2001, develop an artifact standard for EDFA spectral gain.

As we release an SRM for mode-coupled polarization-mode dispersion (PMD), we will direct support to other areas of PMD: we will build and certify a non-mode-coupled PMD artifact, and we will test possible resolution improvements (150 fs reduced to 30 fs) to the modulation phase shift measurement system.

Milestone: By 2000, develop an artifact standard for non-mode-coupled PMD.

System performance is subject not only to the presence of chromatic dispersion (CD), but also its distribution. Techniques currently exist to map CD distribution, but they rely on nonlinear measurement techniques. We are in the process of demonstrating a linear CD mapping technique using RF OTDR.

Milestone: By 2000, demonstrate a linear CD mapping technique using RF OTDR.

Accomplishments

- Characterized 16 Mode-field diameter artifacts (SRM 2513) to 30 nm uncertainty, available for purchase.
- Conducted round robin measurement comparisons for industry participants on fiber mode-field diameter and effective area, EDFA gain and noise figure, VCSEL source characterization (encircled flux), and bandwidth and intersymbol interference for multimode cable/source combinations.
- Developed and demonstrated measurement techniques for overfilled launch zero-dispersion wavelength in multimode fiber. Illustrated the inaccuracy of the customary Sellmeier fit.
- Performed ongoing measurements of differential mode delay on industry supplied multimode fibers.
- Assembled EDFA spectral gain test system and uncertainty characterization begun.
- Demonstrated new simplified and faster algorithm for narrowband PMD measurement using modulation phase shift technique.
- Established capability for special tests of non-mode-coupled PMD with uncertainty of ~ 4 fs.

- Demonstrated new algorithm enabling zero-dispersion wavelength mapping using four wave mixing.
- Identified, in collaboration with industry, VCSEL encircled flux as a reproducible measure of the enhancement to multimode network bandwidth performance.

FY Deliverables

SRMs

NIST SP 260, the SRM catalog, can be ordered through the NIST Standard Reference Material Program. Call (301) 975-6776 or visit <http://ts.nist.gov/srm> to obtain a catalog.

SRM 2513, Mode Field Diameter Standard for Single-Mode Fiber; available, 16 units sent to SRMP in FY 1999

SRM 2520, Optical Fiber Diameter Standard; available.

SRM 2522, Pin Gauge Standard for Optical Fiber Ferrules; available.

SRM 2523, Optical Fiber Ferrule Geometry Standard, available.

SRM 2524, Optical Fiber Chromatic Dispersion Standard, available.

SRM 2553, Optical Fiber Coating Diameter; available.

SRM 2554, Optical Fiber Coating Diameter; available.

SRM 2555, Optical Fiber Coating Diameter; available.

Standards Committee Participation

International Electrotechnical Commission/TC086/SC86C/WG.03, Timothy Drapela is a corresponding member of this working group, which deals with Optical Amplifiers.

Telecommunication Industry Association/FO02/SC.01/WG.01, Timothy Drapela is a member of this working group, which deals with Optical Amplified Devices, Subsystems, and Systems.

Telecommunication Industry Association/FO06/SC.03/WG.03, Timothy Drapela and Matt Young are members of this working group, which deals with Ferrule/Fiber Geometrical Measurement.

Telecommunications Industry Association/FO06/SC.06/WG.01, Timothy Drapela is

chairman and Paul Williams and Matt Young are members of this working group, which deals with Round Robin Testing.

Telecommunication Industry Association/FO06/SC.06/WG.05, Timothy Drapela and Paul Williams are members of this working group, which deals with Single-Mode Fiber.

Telecommunications Industry Association/FO02/SC.02/WG.01, John Schlager is a member of this working group, which deals with Modal Dependence of Bandwidth.

Telecommunication Industry Association/FO02/SC.01: Paul Williams is a member of this subcommittee, which deals with Optical Fiber Communications Systems.

Telecommunications Industry Association/FO06/SC.06: Paul Williams is a member of this subcommittee, which deals with Fiber and Materials.

Telecommunications Industry Association/FO06/SC.03/WG.05: Paul Williams is a member of this working group, which deals with Passive Fiber Optic Branching Devices.

International Standards Organization/TC172/SC.09/WG.07: Matt Young is a member of this working group, which deals with Electrooptical Systems Other Than Lasers.

Telecommunications Industry Association/FO06/SC.03/WG.07: Matt Young is a member of this working group, which deals with Fiber Coatings.

Publications

"Measurements of the Zero-Dispersion Wavelength Fibers Using a Single Low-Cost SLED Source," J.B. Schlager, D.L. Franzen; Tech. Dig., 5th Optical Fibre Meas. Conf., Nantes, France, pp. 133-136 (Sep 99)

"Multimode Fiber Transceiver Launch Distribution: Results of an Industry Round Robin," J. Schlager, M. Hackert, P. Pepeljugoski, M. Murphy, R. Neumann, J. Rice, J. Gwinn; Tech. Dig., 5th Optical Fibre Meas. Conf., Nantes, France, pp. 141-146 (Sep 99)

"Modulation phase-shift measurement of PMD using only four launched polarisation states: a new algorithm," P.A. Williams; Elect. Lett. 35, No. 18, pp. 1578-1579 (Sep 2, 99)

"Mode-Field Diameter of Single-Mode Optical Fiber by Far-Field Scanning: Addendum," M. Young; Appl. Opt. 37, No. 36, p. 8631 (Dec 98)

"Zero-Dispersion Wavelength Distribution in Optical Fiber from CW Four-Wave Mixing," J.B. Schlager; Proc., IEEE Lasers and Electro-Optics Society (LEOS), 11th Annual Mtg. Vol. 2, pp. 309-310 (Dec 98)

Integrated Optics

Technical Contact:
Paul A. Williams

Staff-Years:
1.6 professionals
1.6 graduate students

Funding Sources:
NIST (92 %)
Other Government Agencies (8 %)

Parent Program:
Optoelectronics

Project Goals

Develop and disseminate metrology for the characterization of lightwave planar waveguides.



Norman Fontaine and Matt Young demonstrate the refracted ray scanning system for index of refraction profiling of optical waveguides.

Customer Needs

The constant demand from the lightwave telecommunications market is for higher overall data transmission rates, and many of the key devices that will enable this continuing bandwidth increase are in the form of planar waveguides. The relative youth and explosive growth of lightwave planar waveguide technology presents the need for the development of an associated metrology base.

Technical Strategy

NIST's integrated optics metrology currently centers on two tools: *refracted ray scanning* and *low coherence interferometry*.

Using the method of *refracted ray scanning*, we measure the two-dimensional index of refraction profile across the entrance face of a planar waveguide with a resolution of approximately 4×10^{-5} and an absolute uncertainty of a few

parts in 10^4 . This measurement enables verification of waveguide manufacturing processes and performance prediction. Polarization modulation will enable measurement of the waveguide's birefringence profile. With this capability in place, we can estimate waveguide stresses and polarization-dependent performance of the waveguide. The resolution of the measurement is limited by equipment instabilities, which we can improve or compensate for. Absolute uncertainty is due to batch-to-batch refractive index variations of the index-matching fluids (2×10^{-4} to 5×10^{-4}) and their temperature coefficients; improvements will come in better characterized references.

Milestone: By 2000, demonstrate the measurement of a waveguide's birefringence profile using polarization modulation.

Low coherence interferometry is a useful technique for mapping waveguide properties along their length. This technique is capable of characterizing effective index, length-dependent loss, and Bragg gratings in distributed Bragg reflector lasers. We will use low coherence interferometry to measure effective index to a target uncertainty of 10^{-4} . Noise floor must be reduced to better than -120 dB in order to measure loss coefficients on the order of 0.1 dB/cm. The performance of distributed Bragg reflector (DBR) lasers relies on the quality of the Bragg grating mirror. Low coherence interferometry will be used to characterize gratings; results will be fed back into modeling and manufacturing efforts in cooperation with NIST's Optoelectronic Manufacturing Group.

Milestone: By 2001, measure the effective index of a waveguide with an uncertainty of 10^{-4} .

Accomplishments

- Refracted ray scanning was used in collaboration with the Optoelectronic Manufacturing Group to provide feedback on index profile resulting from thermally-diffused and electric field-assisted techniques of ion-exchanged waveguide fabrication.
- Modified low coherence system for Bragg grating measurements and preliminary measurements made on planar waveguides.

- Developed computer simulation program to emulate the expected results for low coherence measurements on uniform Bragg gratings to study the effects of varying such parameters as the index modulation and grating length. By matching the simulated interferograms with the experimental interferograms, desired parameters such as the index modulation can be determined.

Fiber and Discrete Components

Technical Contact:

Sarah L. Gilbert

Staff-Years:

2.75 professionals

0.5 technician

1.7 post docs

Funding Sources:

NIST Base (40 %)

NIST Non-base (30 %)

Other Government Agencies

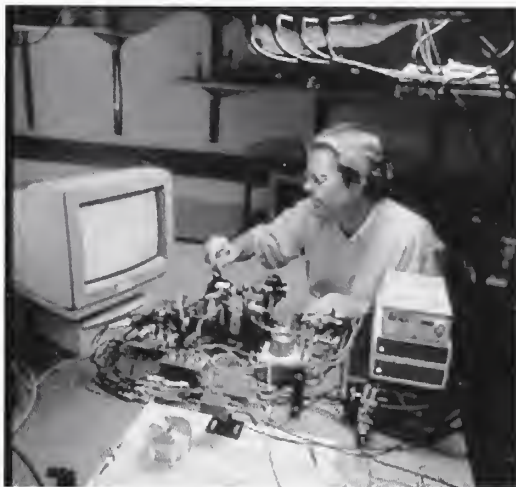
(28 %)

Parent Program:

Optoelectronics

Project Goals

Develop measurement methods for characterization of optical fiber and discrete components, and develop calibration standards needed by industry to calibrate optical fiber test equipment.



Rex Craig adjusting the polarization-dependent loss measurement system.

Customer Needs

The project is concentrating on the needs of the optical fiber communications industry, particularly optical component metrology and wavelength calibration for wavelength division multiplexed (WDM) systems. In a WDM system, bandwidth is increased by sending many channels with different wavelengths down a single optical fiber. WDM systems use a variety of optical components, and new components are under development for next-generation systems. Future systems will likely use narrower channel spacing and a broader wavelength region. For effective system operation, the wavelength and polarization dependence of WDM optical components must be characterized and controlled. Also, the ability of channel filters (multiplexers, demultiplexers, and drop/add filters) to separate channels and minimize crosstalk is a critical factor.

Technical Strategy

Supporting WDM component metrology needs requires developing and evaluating new measurement techniques, disseminating this knowledge, and, when appropriate, developing

Standard Reference Materials to help industry calibrate instrumentation. The project currently focuses on three areas: 1) wavelength standards for WDM, 2) studies of optical fiber photosensitivity (the physical mechanism for producing components such as fiber Bragg gratings), and 3) polarization-dependent loss and wavelength shift metrology.

Wavelength standards are needed to calibrate instruments that measure the wavelengths of sources and characterize the wavelength dependence of WDM components. The project currently produces two wavelength reference Standard Reference Materials: SRM 2517 (acetylene) and SRM 2519 (hydrogen cyanide) that can be used to calibrate the wavelength scale of instruments between 1510 and 1565 nm. WDM will soon expand into other wavelength regions, such as the 1565-1620 nm L band and the 1300-1500 nm region.

MILESTONE: By 2000, provide a high resolution wavelength reference SRM. By 2001, provide a wavelength reference SRM for the WDM L band and develop a high accuracy reference for the 1300 nm region.

New components based on fiber Bragg gratings are being developed and implemented for use as laser wavelength stabilizers, WDM filters, and dispersion compensators. A good understanding of the physical mechanism for producing these devices is needed to predict component behavior. The project is studying the fundamental physical mechanism by which UV light induces an index of refraction change in the core of optical fiber.

MILESTONE: By 2000, conduct NMR measurements of reference samples and UV-exposed fiber preform samples to investigate UV-induced defects in the glass.

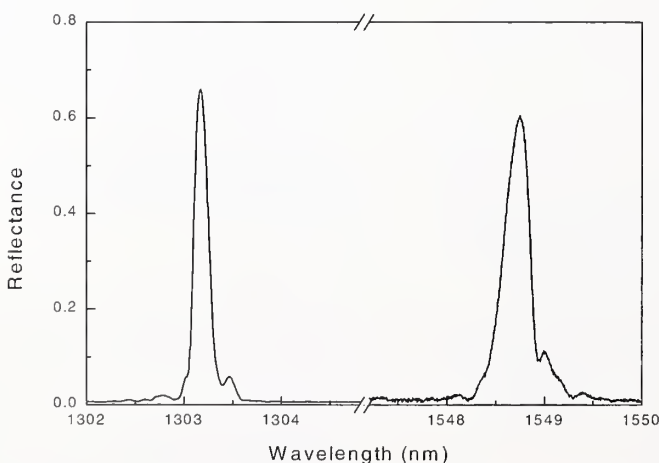
Polarization-dependent loss (PDL) of components and polarization-dependent wavelength shift (PDW) of WDM channel filters must meet increasingly more stringent requirements as the systems become more complex and the channel spacing decreases. The project has developed an accurate PDL measurement system and is now extending this capability to measure PDL wavelength dependence and PDW. In addition, a new SRM is under development to help industry calibrate their PDL measurement instrumentation.

MILESTONE: By 2000, conduct uncertainty analysis of the wavelength-dependent PDL measurement system and produce a PDL SRM. By 2001, develop a PDW measurement system.

Accomplishments

- We completed high-accuracy pressure shift measurements of the 1510-1540 nm transitions of acetylene. We found that there is some variation between the different lines in the spectrum, with greater variation for lines that are far from the branch centers. We have also measured the pressure broadening of the lines and evaluated other line shift mechanisms. These studies were essential for the development of a high-resolution wavelength reference SRM.

- We developed a hybrid wavelength reference device which can provide wavelength calibration references in the visible and near infrared. The device uses multiple fiber Bragg gratings that are superimposed at a specific location in an optical fiber. One grating is actively stabilized to a molecular absorption line and the other gratings are similarly stabilized, since they experience the same controlled environment. These other gratings can have Bragg wavelengths anywhere in the region where the optical fiber is single-mode. Once calibrated, they can then be used as stable wavelength references. This device can provide wavelength calibration capability for spectral regions where there are no reasonable molecular or atomic wavelength references. A provisional patent has been filed for this invention.



Reflectance spectra of superimposed fiber Bragg gratings used in the hybrid wavelength reference device.

- In collaboration with researchers at Colorado State University, we have made preliminary

NMR measurements on UV-exposed fiber preform material. These measurements reveal distinct differences between UV-exposed and non-exposed material and indicate that NMR may be a good tool for studying the UV-induced defects.

- We have developed a wavelength-selective PDL measurement system and have begun measuring of the wavelength dependence of a PDL artifact reference. The system uses a SRM 2519 wavelength reference unit to provide absolute wavelength calibration.

FY Deliverables

SRMs

NIST SP 260, the SRM catalog, can be ordered through the NIST Standard Reference Material Program. Call (301) 975-6776 or visit <http://ts.nist.gov/srm> to obtain a catalog.

SRM 2519, Wavelength Reference Absorption Cell – Hydrogen Cyanide ($\text{H}^{13}\text{C}^{14}\text{N}$); available, 18 units delivered in FY 1999

SRM 2517, Wavelength Reference Absorption Cell – Acetylene $^{12}\text{C}_2\text{H}_2$; available.

Collaborations

Collaboration with the Colorado State University Department of Chemistry NMR Center to conduct NMR studies of UV-induced defects in optical fiber preform material.

Standards Committee Participation

Telecommunication Industry Association/ FO02/SC.01/WG.01: Rex Craig is a member of this working group, which deals with Optically Amplified Devices, Subsystems and Systems.

Telecommunication Industry Association/ FO06/SC.03/WG.05: Rex Craig is a member of this working group, which deals with Passive Fiber Optic Branching Devices.

Telecommunications Industry Association/ FO06/SC.06/WG.01: Rex Craig is a member of this working group, which deals with Round Robin Testing

Telecommunication Industry Association/ FO06/SC.06/WG.03: Rex Craig is a member of this working group, which deals with Sensor Fibers, and which is a joint working group with TIA/FO06/SC.09/WG.03, Sensor Fibers, of which Rex Craig is chair.

Telecommunication Industry Association/ FO06/SC.06/WG.05: Rex Craig is a member of

this working group, which deals with Single-Mode Fiber.

Telecommunications Industry Association/
FO06/SC.09/WG.03: Rex Craig is chair of this sub-committee, Fiber Optic Sensors, and of this working group, Sensor Fibers, which is a joint working group with FO06/SC.06/WG.03.

Telecommunication Industry Association/
FO06/SC.09/WG.04: Rex Craig is a member of this working group, which deals with Polarization Maintaining Connectors.

International Electrotechnical Commission/
TC086/WG.04/SWG5: Sarah Gilbert participates in this working group, which deals with Optical Spectrum Analyzer Calibration.

Publications

"Hybrid Multiple Wavelength Reference Using Fiber Gratings and Molecular Absorption," W.C. Swann, M.A. Hubbard, S.L. Gilbert; Tech. Dig., OSA 1999 Bragg Gratings, Photosensitivity, and Poling in Glass Waveguides, Sep 23-25, 1999, Stuart, FL, pp. ThE6-1/63-65 (Sep 99)

"Nuclear Magnetic Resonance Studies of Hydrogen-Loaded and UV-Exposed Germanosilicate Preforms," M.A. Hubbard, E.M. Gill, S.L. Gilbert, J. Xiong, H. Lock, G.E. Maciel, T. Taunay, M.A. Putman; Tech. Dig., OSA 1999 Bragg Gratings, Photosensitivity, and Poling in Glass Waveguides, Sep 23-25, 1999, Stuart, FL, pp. ThE6-27-0/124-126 (Sep 99)

"Accurate Wavelength Calibration References for Wavelength Division Multiplexing," S.L. Gilbert, W.C. Swann; Tech. Dig., Optical Fiber Communication Conf. (OFC'99), Feb 21-26, 1999, San Diego, CA, Conf. Edition, pp. THS2-1/267-269 (Feb 99)

"Hydrogen Cyanide H¹³C¹⁴N Absorption Reference for 1530 nm to 1560 nm Wavelength Calibration—SRM 2519," S.L. Gilbert, W.C. Swann, C-M. Wang; NISTSP 260-137, NIST Standard Reference Material 2519 (Nov 98)

Optical Fiber Sensors

Technical Contact:

Kent B. Rochford

Staff-Years:

2.25 professionals
0.25 technician
2.5 post docs (1.5 NRC, 1 PREP)
1.0 guest scientist
1.0 PREP (undergrad)

Funding Sources:

NIST Base (60 %)
NIST other (12 %)
Other Government Agencies (23 %)
CRADA (5 %)

Parent Program:

Optoelectronics

Project Goals

Provide basic measurements that support the fiber sensor industry, develop optical component and system standards and measurements, develop advanced prototype sensor technology for other government and industry laboratories, and apply metrology expertise to related optical components.



NIST researchers aligning an optical disc for retardance measurements.

Customer Needs

Optical fiber sensors bring to metrology the same advantages that optical fibers provide to communications. Important advantages include immunity from electromagnetic interference and ease of multiplexing numerous sensors onto a single fiber. As optical fiber sensors are applied to critical applications such as structural monitoring and power generation, the lack of standards and calibrations is becoming evident. Standards are required to ensure the accuracy of systems during typical day-to-day usage as well as assuring reliable measurements over extended times (for example, bridge strain monitoring over decades) that may exceed the lifetime of some measuring subsystems.

This project works to provide traceable standards for optical fiber sensor systems and advance the state-of-the-art in polarimetric current and electromagnetic field sensors and fiber Bragg grating sensors. Because the measurements we develop are not always unique to sensor requirements, we often apply our expertise outside the sensor field when requested. For example, we are extending our fiber Bragg grating measurements to include support for optical fiber communications applications. Recent efforts have assisted manufacturers of optical discs, tempered glass, optical fiber components, and optical fiber test equipment.

Technical Strategy

Our support of optical fiber sensor development and applications requires that we investigate promising system architectures, understand the sources of measurement error, and develop metrology to facilitate the applications of standards. Through our efforts, the Project has developed capabilities in polarimetric and interferometric measurements that are unique within NIST. Where applicable, we strive to apply this metrology expertise to broader optoelectronics needs, and have applied our measurements to a variety of components and applications.

The Project develops advanced prototype sensors for other government agencies and U.S. industry. For example, we have developed current sensors based on annealed optical fiber and have transferred this technology to several U.S. companies. Currently we are developing an advanced fiber-optic sensor based on magneto-optic crystals for the detection of weak magnetic fields. In addition to system design and testing, we also develop specialized components to meet other-agency sensor requirements. Current efforts include the development of a novel fiber-optic mode converter for changing linear polarization to circular polarization and a collaboration to develop high-sensitivity garnet materials.

MILESTONE: By 2001, demonstrate a high-bandwidth, high-sensitivity optical fiber magnetometer that meets other-agency requirements.

Fiber Bragg grating sensors are now used to monitor civil structures, optimize oil and gas extraction from wells, and measure strain in military platforms. Despite the extraordinary measurement conditions and monitoring lifetimes that are envisioned in these applications, few calibrations and standards exist. Strain calibration is especially challenging because interfacial mechanisms may not perfectly transfer strain from the target structure to the sensing fiber. Furthermore, direct calibration of sensors and systems in the field is currently limited by the accuracy of instrumentation available for testing. Fiber Bragg gratings are also widely used as spectral filters in optical fiber communications systems. To support both optical fiber communication and sensor applications, we are developing systems to measure spectral reflectance and transmittance, and are participating in fiber optic standards committees.

MILESTONE: By 2002, develop artifacts with well-characterized spectral reflectance and supporting metrology that can be used to improve the calibration of fiber Bragg grating demodulation/measurement units.

Polarization properties play a role in a variety of optical components and systems. Our project can measure linear retardance with better than 0.1 degree expanded uncertainty and performs special tests at visible and near-infrared wavelengths. Components such as optical discs, liquid crystal modulators, and photolithography masks require retardance measurements over a large spatial area. We are currently developing an imaging polarimeter to provide spatial mapping of retardance. We are also expanding our capabilities to include the measurement of other polarization parameters such as diattenuation, circular retardance, and depolarization.

MILESTONE: By 2000, complete a follow-up round robin of optical disc retardance measurements. By 2002, develop an imaging polarimeter for the routine measurement of retardance, diattenuation, and depolarization with 1 % uncertainty.

The rapid growth of dense wavelength division multiplexing in optical fiber communication systems has greatly increased the need for fast and accurate measurement of fiber component dispersion. Using low-coherence interferometry we have demonstrated measurements of optical path length, group delay, and dispersion in various components. This system can make fiber

Bragg grating dispersion measurements 100 times faster than conventional methods, and provides improved spectral resolution. NIST will extend low-coherence interferometric techniques to support a variety of optical fiber component measurements.

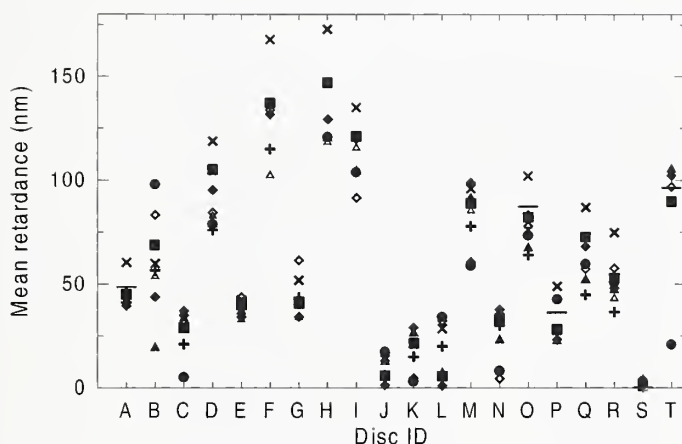
MILESTONE: By 2000, provide customer measurements of group delay and dispersion in fiber Bragg grating filters and other components.

Accomplishments

- We experimentally demonstrated and theoretically explained the influence of the electro-optic Kerr effect on optical fiber current sensor response. The presence of large electric fields may distort the current measurement waveform for some sensor configurations. A demonstration of optical fiber current measurements in a simulated gas-insulated switch environment showed that nominal fields in this device can cause significant distortion.
- In response to industry requests for measurements, we developed and demonstrated a method for measuring dispersion and group delay in waveguide devices using low-coherence interferometry. We have measured fiber Bragg grating group delay with 1 ps repeatability, and this method shows 1.5 ps agreement with the commonly used modulation phase-shift method. Measurements of dispersion, the change in group delay with wavelength, show better than 1 % repeatability (0.02 ps/nm standard deviation for a grating with 7 ps/nm dispersion). A key benefit of our low-coherence interferometry method is the fast measurement time; measurements with 7 pm wavelength resolution are made in one minute compared to the hours required to obtain measurements by use of current methods.
- We coordinated two fiber Bragg grating measurement round robins. For the first intercomparison, five companies pursuing optical fiber communication applications measured spectral reflectance and dispersion. Spectral reflectance measurements showed a variation of 27 pm in center wavelength and 0.5 % in peak reflectance. Measurements of dispersion, a key parameter for communication systems, showed a 16 % range for a 7 ps/nm chirped grating dispersion compensator, indicating the need for improved measurements. A second round robin of spectral reflectance measurements made by five organizations pursuing sensor applications showed 35 pm variation in center wavelength and 1 % variation in peak reflectance. These studies

illuminated weaknesses in industry methods, including disparities in spectral sampling rates and bandwidth definitions that must be standardized to improve measurement agreement.

■ We presented the results of an optical disc retardance measurement round robin performed with the Optical Disc Manufacturing Association. Optical disc specifications require that retardance must be held within 100 nm, and the round robin showed variation of up to 50 nm. We submitted a report to the CD standards authorities that identified error sources in an industry-proposed measurement method and proposed measurement improvements.



Optical disc retardance measurements from 8 instruments on 20 discs.

■ We increased the bandwidth of a fiber-optic magnetometer developed for a government customer to 100 MHz with ± 2 dB ripple. We demonstrated a method for making an optical fiber waveplate (required for sensor optimization) by heating and twisting standard polarization-maintaining fiber.

FY Deliverables

SRMs

NIST SP 260, the SRM catalog, can be ordered through the NIST Standard Reference Material Program. Call (301) 975-6776 or visit <http://ts.nist.gov/srm> to obtain a catalog.

SRM 2525, Optical Linear Retarder, available.

Collaborations

CRADA with Texstar (Grand Prairie, TX) for optical fiber sensors.

Collaboration with Honeywell (now New Phase, Phoenix, AZ) on annealed fiber current sensors.

Collaboration with Optical Disc Manufacturing Association for the measurement of optical disc retardance and other parameters.

Collaboration with Stanford University on optical and magneto-optical measurements of garnet fiber for sensor applications.

Special Services

Special test of retardance in 8 customer-supplied calibration pieces.

Standards Committee Participation

Optical Disc Manufacturing Association: Kent Rochford participates in this trade group, which deals with optical disc measurements.

Telecommunication Industry Association/FO06/SC.03/WG.05: Allen Rose participates in this working group, which deals with Passive Fiber Optic Devices.

Telecommunication Industry Association/FO06/SC.09: Allen Rose participates in this subcommittee, which deals with Fiber Optic Sensors.

External Recognition

Kent Rochford was named an Associate Editor for the Journal of Lightwave Technology.

Publications

"Playing with fire and fibers: annealing optical fiber: application, properties, and dealing with detrimental effects," A.H. Rose; IEEE Circuits and Devices 15, pp. 41-46 (Sep 99)

"Low-coherence interferometric measurements of fiber Bragg grating dispersion," S.D. Dyer and K.B. Rochford; Electronics Letters 35, No. 17, pp. 1485-1486 (Aug 19, 1999)

"Variation in optical disc birefringence measurements," K.B. Rochford, S.K. Kreger, and J. West; Proceedings of SPIE, Joint International Symposium on Optical Memory and Optical Data Storage, 3864, pp. 223-225 (Jul 99)

"Optical fiber current sensors in high electric field environments," A.H. Rose, S.M. Etzel, and K.B. Rochford; J. Lightwave Technology 17, No. 6, pp. 1042-1048 (Jun 99)

"Reconstruction of minimum-phase group delay from fibre Bragg grating transmittance/reflectance measurements," K.B. Rochford and S.D. Dyer; Electronics Letters 35, No. 10, pp. 838-839 (May 13, 1999)

"Demultiplexing of interferometrically interrogated fiber Bragg grating sensors using Hilbert transform processing," K.B. Rochford and S.D. Dyer; J. Lightwave Technology 17, No. 5, pp. 831-835 (May 99)

Dielectric Materials and Devices

Technical Contact:
Norman A. Sanford

Staff-Years:
3.5 professionals
2.0 post-docs

Funding Sources:
NIST base (73 %)
NIST non-base (15 %)
Other Agency (12 %)

Parent Program:
Optoelectronics

Project Goals

Maintain and evolve methods of nonlinear optics for uniformity measurements that support manufacturing metrology for photonic materials. Perform characterization and spectroscopy, and to explore optical waveguide fabrication methods in rare-earth doped laser glass. Develop compact solid state waveguide lasers for optical telecommunication metrology and high-speed optical A/D conversion. Develop modeling, fabrication, and metrology methods for photonic crystals and single photon turnstile devices.



Nonlinear optical measurement system for nondestructive mapping of composition, strain, refractive index, and thickness in materials including lithium niobate and gallium nitride.

Customer Needs

Customer needs fall into four main categories: 1) development of metrology suites for rapid non-destructive characterization of photonic materials, 2) compact, stable, and inexpensive lasers for optical telecommunications metrology, 3) emerging worldwide needs for ultrafast optical A/D conversion technologies, and 4) development of new competence in the areas of photonic crystals, spontaneous emission control of quantum dots, and single photon turnstile devices.

LiNbO₃ is the material of choice for the fabrication of high-speed (~10 GHz) optical modulators. These devices are in increasing demand for the rapid global expansion of wavelength-division multiplexed (WDM) optical telecommunication systems. Notably, in 1999 the installation rate of 10 gigabits per second fiber optic communication systems increased to

approximately 8000 per year, and all of these systems required LiNbO₃ modulators.

Accordingly, NIST receives numerous requests for LiNbO₃ evaluation services. The success of our nonlinear optical characterization of LiNbO₃ has led in a very natural way to extending this work into other important photonic materials, such as GaN and AlGaAs. GaN has made enormous recent economic impact with the realization of semiconductor lasers and LEDs emitting in the blue. Other important applications of this material include high-power high-temperature transistors and solar-blind UV detectors. Frustrating these application demands, however, problems with bulk and thin film growth of these materials remain, and thus developing new metrology methods is crucial. AlGaAs is a well-established and important material, but nevertheless there are increasing industry demands for more precise and reliable *in situ* and *ex situ* metrology methods.

Compact diode-pumped solid state laser devices are emerging as an important technology with impact ranging from telecommunication to high-speed signal processing. With assistance from corporate and DARPA collaborators, NIST has been on the cutting edge of developing this technology and is assisting in its commercialization in both of these application areas.

Finally, the new areas of photonic crystals, spontaneous emission control of quantum-confined structures, and single photon turnstile devices are opening up exciting opportunities for quantum cryptography, quantum optics, and optical telecommunications.

Technical Strategy

Nonlinear optics offer rapid and versatile measurement capabilities that are not readily duplicated by more conventional metrologies. For example, in our work with the characterization of LiNbO₃ we have developed methods for fully non-destructive evaluation of composition and strain in finished wafers of the material. Studying wafers cut sequentially from full boules has allowed us to track these quantities and relate them to growth conditions of large crystals. Furthermore, the results of the nonlinear optical investigations correlate with

"Schott Glass Technologies Inc. would like to express to you our continued commitment to the CRADA activity between our two organizations. This work, which first began in 1992, has opened the door to many exciting opportunities for our company in the area of active materials for guided wave optical devices..... We look forward to the commercialization of the technology developed in the CRADA and to continuing our interaction together in the future."

Joseph S. Hayden, Manager,
R&D Materials Group
Schott Glass Technologies

ongoing collaborations with NIST MSEL involving high-resolution X-ray diffraction imaging. The success of the nonlinear optical characterization of LiNbO_3 has led in a very natural way to extending this work into other important photonic materials such as GaN and AlGaAs.

MILESTONE: By 2000, reconstruct the existing nonlinear optical characterization system to permit agile switching between pulsed pump wavelengths near 1800 nm, 1064 nm, and 800 nm. This will enable a rapid response to industrial characterization needs of industry for a wide range of photonic materials.

MILESTONE: By 2001, establish nonlinear optical characterization methods for thin film and bulk GaN and thin film AlGaAs.

The work on compact solid state waveguide lasers will continue to rely on our successful ongoing collaboration with Schott Glass Technologies in refining metrology methods and laser design that lead toward fully optimized glass compositions. The optimization issues are concerned with rare-earth doping, spectroscopy, and glass chemistry enabling optical waveguide fabrication. The significance of this work falls primarily into two areas. Firstly, the specialty laser glasses jointly developed by Schott and NIST are enabling NIST to fabricate extremely stable and efficient distributed-Bragg reflector (DBR) lasers that have immediate application in metrology testbeds for wavelength-division multiplexed (WDM) telecommunication systems. Secondly, DARPA is partially funding the NIST work in developing ultrafast passively mode-locked lasers in these glasses. The application area is all-optical A/D conversion technology. This work will also enable NIST to contribute to establishing an industry standard for ultrafast jitter. Such standards are currently in demand but unavailable.

MILESTONE: By 2000, develop arrayed distributed Bragg reflector (DBR) lasers with output wavelengths conforming to the International Telecommunication Union (ITU) grid.

MILESTONE: By 2000, perform waveguide characterization and DBR fabrication studies on special multi-constituent rare-earth doped glasses.

MILESTONE: By 2000, develop new semiconductor saturable absorber mirror structures, demonstrate prototype passively mode-locked solid state waveguide lasers, and work toward optimized laser glass for this special application.

MILESTONE: By 2002, demonstrate fully monolithic, passively mode-locked solid state waveguide laser operating at 10 GHz.

A new research effort will rely on the key areas of photonic crystal modeling, photonic crystal fabrication, growth and electrical contact to single quantum dots, and integration of quantum dots with single-electron pumps.

MILESTONE: By 2000, set up laboratory for cryogenic spectroscopy of quantum dots.

MILESTONE: By 2000, construct chemically-assisted ion-beam etching system.

MILESTONE: By 2001, establish methods of cryogenically reliable electrical contacts to individual quantum dots.

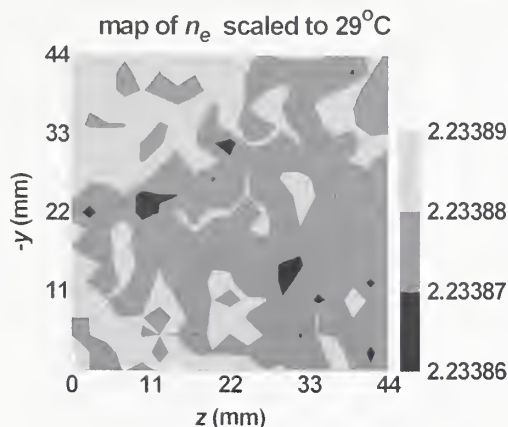
MILESTONE: By 2002, establish design and fabrication methods for photonic crystals.

Accomplishments

■ The nonlinear optical analysis work on x- and z-cut LiNbO_3 has revealed composition gradients along the direction of growth in full LiNbO_3 boules. A composition variation of roughly 0.02 mol % Li_2O between the top and bottom of a boule was measured. This result is significant for two reasons: (1) This composition variation translates directly into a birefringence variation of approximately 2×10^{-4} between the top and bottom of the boule; (2) With current crystal growth methods commonly used, it is not possible to predict if a boule will grow Li rich or Li depleted. The nonlinear optical analysis provides a rapid means to make such a determination by simply performing single Maker fringe scans separately on wafers cut from the extreme ends of the boule. In addition, the analysis has also provided the means to correct the Sellmeier equations and temperature dependence of the Sellmeier equations for this material.

■ The nonlinear optical analysis for both x- and z-cut LiNbO_3 was generalized to consider fully resonant multiple passes of the pump and second harmonic generation. The work has permitted alternative methods of measuring index of refraction, nonlinear optical coefficients, and dc electrooptic coefficients in the material. It is also reducing the ambiguity in these quantities, to a few parts in 10^4 in the case of refractive index. It should be noted, however, that the method clearly resolves birefringence variations on the

order of few parts in 10^5 . The length scale of the material perturbation detected is a few percent of the coherence length of the second harmonic



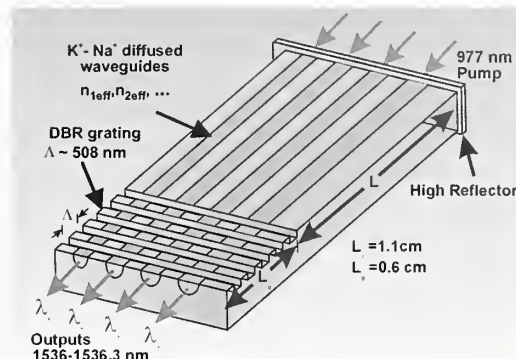
generation.

Contour map showing the variation of the extraordinary index of refraction n_e at 532 nm over a 76 mm diameter x-cut lithium niobate wafer. The data has been scaled to a temperature of 29 °C. The map is composed of 361 points arranged on a square grid with a mesh of 2.444 mm and covers a 44 mm² region centered on the wafer. Axes y and z refer to the crystalline axes of the wafer. The index gradient, oriented along z, conforms to the sense of the poling field that was used to force the host crystal into a single ferroelectric domain.

■ Nonlinear optical analysis was extended to examine the uniformity of GaN bulk crystals grown by high-pressure processing and thin films of the material grown by HVPE and MOCVD. The results show a distinct progression in both the index of refraction and the magnitude of the nonlinear optical coefficients in progressing from the bulk material to the MOCVD thin film material.

■ Arrays of single-frequency, distributed-Bragg-reflector waveguide lasers with distinct output wavelengths near 1536 nm were fabricated on Er/Yb-doped glass substrates. The devices exhibited record slope efficiencies of 26 %, 80 mW output power for 350 mW of launched pump power at 977 nm, and emission linewidths of 500 kHz. Relative intensity noise (RIN) measurements of diode-pumped lasers yielded RIN values of less than -150 dB/Hz for frequencies above ~0.5 GHz, comparable to those of semiconductor DFB lasers. The wavelength variation of the lasers as a function of temperature is roughly 15 times smaller than that of typical semiconductor DFB lasers. A reliable fabrication process was developed in collaboration with a CRADA partner. The

compactness, high stability, and spectral purity of glass waveguide lasers, and the large gain bandwidth of the doped glass, make the technology very suitable for dense wavelength-division-multiplexing systems metrology and



detector frequency response measurements.

Distributed-Bragg-reflector waveguide laser array realized using a single pitch grating and diffused waveguides with varying effective index.

FY Deliverables

External Recognition

Norman Sanford was named an Associate Editor for the IEEE Journal of Quantum Electronics.

Publications

"Erbium and Ytterbium Waveguide Lasers in Phosphate Glass," D.S. Funk, P.M. Peters, D.L. Veasey, N.A. Sanford, J.S. Hayden; OSA TOPS on Advanced Solid-State Lasers 26, pp. 157-159; Tech. Dig., OSA ASSL, pp. WA5/1-3/294-296 (99)

"Ion-Exchanged Er³⁺/Yr³⁺ Glass Waveguide Lasers in Silicate Glass," P.M. Peters, D.L. Veasey, D.S. Funk, N.A. Sanford, S.N. Houde-Walter, J.S. Hayden; OSA TOPS on Advanced Solid State Lasers 26, pp. 160-162; Tech. Dig., OSA ASSL, pp. WA6/1-3/297-299 (99)

"Laser Arrays May Provide DWDM Measurement Tool," D.L. Veasey, D.S. Funk, N.A. Sanford, J.S. Hayden, M. Bendett; Laser Focus World 35, No.5, pp. 203-210 (May 99)

"Erbium/Ytterbium-Codoped Glass Waveguide Laser Producing 170 mW or Output Power at 1540 nm," D.S. Funk, D.L. Veasey, P.M. Peters, N.A. Sanford, N.H. Fontaine, J.S. Hayden; Tech. Dig., OFC '99, pp. TuC5-1/32-34 (Feb 99)

"Arrays of Distributed-Bragg-Reflector Waveguide Lasers at 1536 nm in Yb/Er Codoped Phosphate Glass," D.L. Veasey, D.S. Funk, N.A. Sanford, J.S. Hayden; Appl. Phys. Lett. 74, No. 6, pp. 789-791 (Feb 8, 99)

"Nonlinear Optical Characterization of LiNbO₃. I. Theoretical Analysis of Maker Fringe Patterns for X-Cut Wafers," N.A. Sanford, J.A. Aust; J. Opt. Soc. Am. B 15, No 12, pp. 2885-2909 (Dec 98)

Semiconductor Materials and Devices

Technical Contact:
Robert K. Hickernell

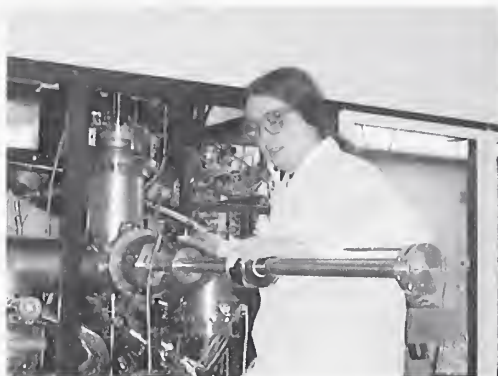
Staff-Years:
4.5 professionals
1.0 technicians
1.5 graduate students

Funding Sources:
NIST base (81 %)
NIST non-base (13 %)
Other agency (6 %)

Parent Program:
Optoelectronics

Project Goals

Support the compound semiconductor optoelectronics industry with advanced measurement methods, services and standards, and fabricate custom devices to support optoelectronics metrology and research at NIST.



Gas-source molecular beam epitaxy system for III-V semiconductor growth and *in situ* growth monitoring research.

Customer Needs

The rapid growth of the U.S. optoelectronics industry is dependent on the high-yield manufacture of devices with increasingly tight specifications. Compound semiconductor materials form the basis for LEDs, lasers, photodetectors, and modulators critical to optical communication, display, data storage, and many other applications. Materials purity and uniformity issues are at the foundation of device yield and performance. Measurements of starting material and epitaxial layers must be supported by standard procedures and reference materials. Increasingly the needs are for accurate in-process measurements. In addition, specialty devices are needed for use in metrology systems inside and outside of this project.

Technical Strategy

Inaccuracy of semiconductor composition measurement has been an impediment to achieving consistency of device performance across production lines and the collection of sufficiently accurate materials parameters for use in the simulation of devices, all of which are critical to fast product cycle time. The problems have been exacerbated by the increase in outsourcing of epitaxial growth. A goal of this project is to develop certification techniques for

standard reference materials that have compositions specified to better than 1 % uncertainty, for example $\text{Al}_x\text{Ga}_{1-x}\text{As}$ with $x=0.20 \pm 0.002$. This represents approximately a ten-fold improvement over the accuracy of techniques currently in use by industry. We will achieve this goal by monitoring the time evolution of the film properties during epitaxial growth to collect new and independent information to correlate with *ex situ* characterization. Some of the tools we are currently utilizing or developing in this cross-division collaborative program are reflection high-energy electron diffraction (RHEED), *in situ* optical reflectance spectroscopy (ORS), *in situ* atomic absorption, photoluminescence (PL), x-ray diffractometry (XRD), and electron micro-probe analysis (EMPA). One thrust of our approach is the quantification of the accuracy limits of the indirect composition measurement techniques currently in use by industry, specifically PL and XRD. Another thrust is the demonstration of the composition accuracy that can be achieved with direct microanalytical techniques such as electron micro-probe analysis (EMPA) in combination with accurate reference artifacts.

MILESTONE: By 2001, develop AlGaAs composition standards with mole fraction uncertainty measured to 1 %.

MILESTONE: By 2002, develop InGaAsP composition standards with mole fraction uncertainty measured to 1 %.

Contamination is a serious problem in source gases used in the epitaxial growth of high purity semiconductor layers. Device manufacturers have expressed frustration with the irreproducibility of source material purity from vendor lot to vendor lot and as the vendors change process or packaging. The issue is described by industry as primarily a measurement problem in that manufacturers frequently report impurity levels as "not detected" for a series of lots that produce very different device results. The critical concentrations of the impurities are not well known, but it is believed that >10 ppb oxygen or water in phosphine is undesirable. In collaboration with researchers in the NIST Chemical Science and Technology Laboratory (CSTL), this project is developing a cavity ring-down spectroscopy technique to measure

impurities with very low concentrations in semiconductor source gases. The advantages of this technique are that its accuracy relies primarily on accurate time measurement and detector linearity and that it is insensitive to absorption outside the cavity. The initial focus is on measuring water content in phosphine gas.

MILESTONE: By 2001, develop and prove cavity ring-down technique for measuring water in phosphine to 1 ppb, calibrated to humidity standards.

The measurement of detector spectral responsivity is a service performed by the Division. To provide this service with wider applicability and impact, there exists a need to replace both lasers that emit at discrete wavelengths and broadband lamp sources that have low output intensity with compact, broadly tunable lasers. We are developing semiconductor quantum well and quantum dot lasers that will allow us to reach the wavelength ranges in between those of commercially available devices.

MILESTONE: By 2001, develop infrared tunable lasers with 100-300 nm tunability.

Microstructural characterization of materials is especially important to the development of rapidly growing technologies, such as those based on group-III nitrides or quantum dots. The emphasis on achieving record device performance often leaves behind the basic measurements needed to understand the long-term viability of the technologies. We are applying techniques based on atomic force microscopy (AFM) and transmission electron microscopy to study growth mechanisms, uniformity, surface morphology, and defect structure in semiconductor material. These measurements are correlated with optical and high-resolution x-ray measurements in a collaborative cross-division program.

MILESTONE: By 2000, characterize the density and size uniformity of semiconductor quantum dots as a function of growth conditions. Characterize the surface structure of gallium nitride grown by a variety of methods.

Native oxide layers are used as carrier confinement layers, broadband antireflection (AR) coatings and/or lenses in vertical cavity surface emitting lasers (VCSELs), photodetectors, light emitting diodes, and saturable Bragg mirrors. Yet many of the material parameters necessary for predictable, reproducible layer formation remain

uncharacterized. To address these issues, we are measuring the oxidation rate of buried AlGaAs layers as functions of Al concentration, layer thickness, crystallographic direction, and growth technique.

MILESTONE: By 2000, characterize the oxidation of buried AlGaAs.

Accomplishments

- Three independent methods of measuring compound semiconductor composition were shown to agree remarkably well, to within an uncertainty of 2 %. To achieve this level of *in situ* accuracy, modifications were made to both the substrate manipulator and *in situ* ORS system on the molecular beam epitaxy (MBE) system to reduce ORS signal noise and the uncertainty of absolute reflection intensity. A set of specimens spanning the range of Al mole fraction from 0.00 to 1.00 was grown while acquiring data using ORS and *in situ* RHEED. This set was examined with electron micro-probe analysis (EMPA) by collaborators in NIST CSTL. The data revealed that, using a single standardized correction procedure, the EMPA composition measurements agreed with the MBE *in situ* measurements to within ± 2 % relative.

- A "smart" pyrometry system was developed that monitors the substrate temperature during MBE growth. It avoids the skewing of temperature readings due to epitaxial film growth by measuring both the actual emissivity (derived from reflectance) of the sample and the infrared emission intensity. Differences in apparent temperature as measured by the smart and conventional pyrometers are as large as 20 °C during the growth of a distributed Bragg reflector. A new optical configuration also extended the lowest measurable GaAs temperature from 525 °C to 400 °C. The extended temperature range is critical to the growth of InGaAsP layers for the development of composition standards.

- The height of buried AlGaAs layers, oxidized under ambient conditions, was measured by atomic force microscopy as a function of both Al composition and time. The increase in layer height with Al composition appears to follow an exponential function up to 80 % Al. The oxidation of layers with 40 % or less Al is very small after 23 hours (a height increase of 0.1 nm or less) and does not change appreciably over the next 21 hours. This and future data will be used to determine which, if

any, of the composition standards must be capped to prevent changes over time.

- In preparation for water impurity measurements in phosphine, a second ring-down cavity was assembled in a ventilated and monitored enclosure in the project labs. The optical layout is similar to the original ring-down cavity system built as a part of this joint program by CSTL collaborators. The CSTL cavity was used to measure residual water spectra in vacuum as a demonstration that the simplified methods chosen for tuning the cavity and triggering data acquisition will be adequate for this experiment.

- Broadband antireflection (AR) coatings based on the wet thermal oxidation of AlGaAs were developed and characterized. Surface oxide AR coatings were demonstrated experimentally having reflectance <1 % over >250 nm around a center wavelength near 1000 nm. Buried oxide coatings with a zero reflectance minimum and <1 % reflectance bandwidth of >150 nm were simulated. The native oxidation technique simplifies manufacturing by avoiding evaporation or sputter deposition after the semiconductor epitaxy.

- The oxidation front of AlGaAs native oxide lenses in VCSELs was characterized by atomic force microscopy. The AFM showed a height difference between the oxidized and unoxidized regions consistent with the contraction of the wet oxidized layers relative to AlGaAs. In addition, a 13 % difference was found between the distance the oxidation front had traveled along different crystallographic directions. This difference may prove important for producing oxide lenses of controlled shapes.

- The spatial and spectral characteristics of the transverse modes of VCSELs were studied from near-field scanning optical microscopy (NSOM) measurements made at Boston University. Proton implanted devices used in 2 gigabits per second multimode fiber optic links were investigated. Lasing filaments were observed at high drive currents. Spatially overlapping transverse modes competed for available gain while spatially separated modes did not. NSOM is a powerful technique for contributing to the understanding of how the modal patterns of VCSEL emission affect system performance in high-speed data links.

- InGaAs in-plane lasers with staggered quantum well widths were fabricated and operated with output wavelengths near 1.0 μm .

The specialty lasers are being developed for broad wavelength tuning in an external cavity, to be used for the measurement of the spectral responsivity of detectors.

- A procedure was developed for growing highly uniform arrays of InGaAs quantum dots with peak emission in the range of 1130 to 1330 nm. AFM measurements showed that the size distribution changes from bimodal to unimodal as the quantum dots grow larger. Room-temperature photoluminescence measurements of the unimodal sample indicated a linewidth of 18 meV FWHM for the ground state emission at 0.93 eV (1330 nm). This corresponds to a record fractional linewidth ($\Delta E/E$) of 1.9 %, smaller than typical linewidths reported in the literature for this emission energy by a factor of about 1.5. High uniformity in quantum dot size distribution, as indicated by the narrow emission linewidths and measured by AFM, is important for the fabrication of low-threshold, temperature-insensitive laser diodes. This work supports the development of tunable quantum dot lasers for detector spectral responsivity measurements and the development of low-density arrays of quantum dots for photonic turnstiles.

FY Deliverables

Publications

- "Spatio-Spectral Mapping of Multimode Vertical Cavity Surface Emitting Lasers," K.J. Knopp, D.H. Christensen, G.H. Vander Rhodes, J.M. Pomeroy, B.B. Goldberg, M.S. Ünlü; *J. Lightwave Tech.* 17, No. 8, pp.1429-1435 (Aug 99)
- "Photon Statistics of Pulsed, Vertical-Cavity, Surface-Emitting Lasers," M. Beck, T.W.S. Garrison, D.H. Christensen; *Tech. Dig., OSA Ultrafast Electronics and Optoelectronics*, pp. QMD5-1/52-54 (Apr 99)
- "High-Speed >90 % Quantum-Efficiency P-I-N Photodiodes with a Resonance Wavelength Adjustable in the 795-835 Range," E. Özbay, I. Kimukin, N. Biyikli, O. Aytür, M. Gökkavas, G. Ulu, M.S. Ünlü, R.P. Mirin, K.A. Bertness, D.H. Christensen; *Appl. Phys. Lett.* 74, No. 8, pp. 1072-1074 (Feb 22, 99)
- "AlInP Benchmarks for Growth of AlGaInP Compounds by Organometallic Vapor-Phase Epitaxy," K.A. Bertness, S.R. Kurtz, S.E. Asher, R.C. Reedy, Jr.; *J. Crystal Growth* 196, pp. 13-22 (Jan 99)
- "Cation Vacancy Formation and Migration in the AlGaAs Heterostructure System," P. Mitev, S. Seshadri, L.J. Guido, D.T. Schaafsma, D.H. Christensen; *Appl. Phys. Lett.* 73, No. 25, pp. 3718-3720 (Dec 21, 98)
- "Optical Constants of (Al_{0.98}Ga_{0.02})xOy Native Oxides," K.J. Knopp, R.P. Mirin, D.H. Christensen, K.A. Bertness, A. Roshko, R.A. Synowicki; *Appl. Phys. Lett.* 73, No. 24, pp. 3512-3514 (Dec 14, 98)

Appendix A: Major Laboratory Facilities

Semiconductor Growth and Optoelectronic Device Fabrication

The Division makes use of a gas-source molecular beam epitaxy system and associated *in situ* and *ex situ* measurement equipment for III-V semiconductor growth and characterization. It also maintains a cleanroom facility for thin film deposition, photolithography, and wet and dry etching. The facilities support the activities described above for the Dielectric Materials and Devices Project and the Semiconductor Materials and Devices Project.

Laser Power/Energy Detector Calibration Systems

The Optoelectronics Division has established and maintains several state-of-the-art measurement systems for calibrating most types of laser power and energy detectors. These measurement systems incorporate unique, specially designed, electrically calibrated, laser calorimeters that are used as primary standards. The calorimeters are used in conjunction with beamsplitter-based optical systems to provide measurement services for laser power and energy that cover a wide range of powers, energies, and wavelengths for detectors used with both cw and pulsed lasers. This assembly of laser power and energy detector calibration systems represents the best overall capability of this kind in the world. In many cases (e.g., excimer laser measurements at 248 nm and 193 nm), the Division has the only measurement capability in the world.

Appendix B: NRC Postdoc and Other Research Opportunities

National Research Council Associateship Opportunities

The National Institute of Standards and Technology (NIST), in cooperation with the National Research Council (NRC), offers awards for postdoctoral research in many fields. These awards provide a select group of scientists and engineers an opportunity for research in many of the areas that are of deep concern to the scientific and technological community of the nation. NIST, with direct responsibilities for the nation's measurement network, involves its laboratories in the most modern developments in the physical, engineering, and mathematical sciences and the technological development that proceed from them.

The Research Council, through its Associateship Programs office, conducts an annual national competition to recommend and make awards to outstanding scientists and engineers at the postdoctoral level for tenure as guest researchers at participating laboratories. The deadline for applications is January 15 for appointments beginning between July 1 and the following January 31.

The objectives of the Programs are:

- to provide postdoctoral scientists and engineers of unusual promise and ability opportunities for research on problems, largely of their own choosing, that are compatible with the interest of the sponsoring laboratories
- to contribute thereby to the overall efforts of the federal laboratories

Eligibility requirements include U.S. citizenship and receipt of Ph.D. within 5 years of application. NRC positions involve a two-year tenure at NIST, and the 1999 salary paid was \$48,500.00.

For more detailed information, including instructions for applicants, please contact the Optoelectronics Division Office and request a copy of the NRC Postdoctoral Opportunities booklet. You may also visit the NRC Research Associateship Program Optoelectronics Division webpage (<http://national-academies.org/rap>) to see a list of opportunities within our division.

1999 opportunities with the Optoelectronics Division through the NRC Research Associateship program:

- | | |
|----------------------------------------------------------------------------------|------------------------------------------------------------------------------------------|
| ■ Optical Fibers and Integrated Optics | ■ Quantum Limited Laser Linewidths |
| ■ Dimensional Characterization of Optical Waveguides | ■ <i>In-Situ</i> Metrology of Epitaxial Crystal Growth for Semiconductor Optoelectronics |
| ■ Nonlinear Properties of Single-Mode Optical Fiber | ■ Vertical-Cavity Optoelectronics |
| ■ Multimode Optical Fiber Bandwidth | ■ Strained Heteroepitaxy for Compound Semiconductor Optoelectronics |
| ■ Materials Characterization for Optoelectronics | ■ High Speed Optoelectronics Measurements |
| ■ Optoelectronic Materials Characterization by cw and Ultrafast Nonlinear Optics | ■ Deep Ultraviolet Laser Metrology |
| ■ Ultrafast Widely Tunable Coherent Infrared and Ultraviolet Parametric Sources | ■ Fiber and Discrete Components |
| ■ Femtosecond Metrology for Compact Photonic Devices | ■ Optical Data Storage |
| | ■ Optical Fiber Sensor Systems |
| | ■ Polarization Metrology |

Professional Research Experience Program (PREP)

The Professional Research Experience Program (PREP) is designed to provide valuable laboratory experience to undergraduate and graduate students from the University of Colorado at Boulder and from the Colorado School of Mines at Golden, and to recent Ph.D. recipients from these and other universities. Students and post-docs are employed by the University of Colorado or the Colorado School of Mines and normally carry out research at the NIST Boulder Laboratories.

Students are usually hired just before the spring, fall, or summer terms, and may be employed for one or more terms. Post-docs may begin any time during the year. Applications are accepted throughout the year.

NIST pays in-state tuition for PREP undergraduate students during the fall and spring semesters and an hourly wage. Graduate students receive in-state tuition and a stipend. Postdocs receive a stipend.

Eligibility requirements include U.S. citizenship or permanent residency and, for students, a minimum 3.0 GPA (grade point average).

An application form and further information are available from:

Phyllis Wright, Student Outreach Coordinator
NIST, MC 360
325 Broadway
Boulder, CO 80303
Phone: (303) 497-3244

Appendix C: Conferences and Workshops

Symposium on Optical Fiber Measurements

The Optoelectronics Division, in cooperation with the Optical Society of America and the IEEE Lasers and Electro-Optics Society, organizes the biennial Symposium on Optical Fiber Measurements held in Boulder in the fall of even-numbered years. This Symposium is a 2 ½ day meeting devoted entirely to the topic of measurements on fiber, related components, and systems. It provides a forum for reporting the results of recent measurement research and an opportunity for discussions that can lead to further progress. It consists entirely of contributed and invited papers.

Experimental and analytical papers on any measurement aspect of guiding lightwave technology are solicited for the Symposium. Examples include measurements on:

Fibers and fiber components

Telecommunications fiber

Fiber lasers and amplifiers

Fibers for sensors

Couplers

Connectors

Multiplexers

Non-fiber components

Systems

Field and laboratory instrumentation

Standards

A limited number of Digests from previous Symposia are available. For information on obtaining a Digest or for information on upcoming Symposia, please contact the Optoelectronics Division Office or visit our web page, <http://www.boulder.nist.gov/div815/current.html>.

Laser Measurements Short Course

The Optoelectronics Division, in cooperation with the University of Colorado at Boulder, offers an annual Short Course on Laser Measurements. The 3 ½ day course emphasizes the concepts, techniques, and apparatus used in measuring laser parameters. A tour of the NIST laser measurement laboratories is included. The faculty consists of laser experts from NIST, industry, and other government agencies. A degree in physics or electrical engineering or equivalent experience is assumed, and some experience in the use of lasers is desired for attendees.

Appendix D: Cooperative Research and Development Agreements (CRADAs)

CRADA Title: Optical and Structural Examination of GaN Thin Films and Processing of GaN Devices

CRADA Partner: Astralux, Inc.; Boulder, CO

NIST Principal Investigator(s):

Norman A. Sanford

Exp. Date and Status: 5/11/00; Active

CRADA Title: Rare-earth-doped Waveguide Laser Structures

CRADA Partner: Schott Glass Technologies, Inc.; Duryea, PA

NIST Principal Investigator(s):

Norman A. Sanford

Exp. Date and Status: 10/08/00; active

CRADA Title: Optical Fiber Electric Field Sensors

CRADA Partner: Texstar, Inc.; Grand Prairie, TX

NIST Principal Investigator(s):

Allen H. Rose

Exp. Date and Status: 5/21/00; active

CRADA Title: Analysis of Lithium Niobate Wafers

CRADA Partner: Crystal Technology, Inc.; Palo Alto, CA

NIST Principal Investigator(s):

Norman A. Sanford

Exp. Date and Status: 10/28/98; expired

CRADA Title: Absorption Cell Technology

CRADA Partner: Environmental Optical Sensors, Inc.; Boulder, CO

NIST Principal Investigator(s):

Sarah L. Gilbert; David Nesbitt (Div. 848)

Exp. Date and Status: 12/28/98; expired

CRADA Title: Eye-Safe Q-Switched Solid State Lasers

CRADA Partner: Northstar Photonics, Inc.; Plymouth, MN

NIST Principal Investigator(s):

Norman A. Sanford

Exp. Date and Status: 9/30/99; expired

January 2000

For additional information contact:

Telephone: (303) 497-5342

Facsimile: (303) 497-7671

On the Web: <http://www.boulder.nist.gov/div815>